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GUNHARDENED CRYSTAL OSCILLATORS FOR REMOTELY MONITORED BATTLEFIELD SENSOR SYSTEM

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GUNHARDENED CRYSTAL OSCILLATORS FOR REMOTELY MONITORED BATTLEFIELD SENSOR SYSTEM

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October 1976

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The genesis of a temperature compensated voltage controlled (for FSK modulation) crystal oscillator capable of maintaining a 5 ppm accuracy in either FSK state (mark and space) under conditions of 15,000g shock, -40°C to +75°C ambient temperature and aging for one year is described. The thick film microcircuit oscillator occupies less than 0.5 cubic inches and consumes less than less than 50 mW of power.

The development of the requisite crystal unit required a large number of design and processing innovations whose significance, aside from the shock resistance

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20. transcends their immediate application to the REMBASS oscillator. Among them is a new family of microcircuit compatible ceramic flatpack crystal enclosures; a laser assisted X-ray goniometer for precision angle measurements; novel surface preparation and cleaning procedures definitized with the aid of high energy electron diffraction, scanning electron microscopy and Auger spectroscopy; and the concept of a novel in-line, ultrahigh vacuum processing facility to assure long term stability. Finite element computer studies aided in the shockproofing of the resonators, and 20 MHz crystal units that survived 36,000g shock and remained within the assigned frequency tolerance at 15,000g have been fabricated.

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INTRODUCTION

Since the concept of using sensors to detect enemy movements was first employed in Southeast Asia, the Department of Defense has been actively interested in advancing sensor technology (1).. Each service made use of various sensor systems for either tactical or fixed installation missions.

Army development efforts have been concerned primarily with tactical applications of sensors, and the responsibility for this program has been assigned to the Office of the Project Manager REMBASS. The acronym REMBASS is derived from the words "Remotely Monitored Battlefield Sensor System". Two projects under the cognizance of this Project Manager are relevant to this discussion: these are called REMBASS, already defined, and the other is FAALS - which is an acronym for "Field Artillery Acoustic Locating System". Both systems use similar data transmission systems for providing sensor derived information to a remote intelligence gathering station. Both systems employ sensors emplaced by various means, but the artillery delivered sensors are of concern here. The heavy dependence on gun emplaced sensors requires reliable sources for production quantities of units built to withstand an unusually severe environment. Of the several electronics packages comprising the complete sensor, the one which could not be built in sizable quantities, with any predictable performance, is the oscillator. In order to establish a source, innovative manufacturing techniques, completely defined, would first have to be developed. Such an R&D effort was undertaken by the US Army Electronics Technology and Devices Laboratory (ECOM), supported by the Project Manager REMBASS.

The magnitude of the technical problems to be overcome by the program can be appreciated by contemplating Figure 1, depicting the actual deployment of the sensor. In addition to the worldwide temperature requirements (-40°C to +75°C), the oscillator, with its crystal, must withstand the rigors of the trajectory shown, and maintain a stability of 5 ppm.

A special shell, housing all the sensor components in a separable missile called the Terminal Delivery Vehicle (TDV), is fired from a 155 mm gun. This imparts a shock of some 15,000g with a rotational acceleration of 332,000 rad/sec^2. After a pre-determined interval along the trajectory, a time fuze activates a charge, causing separation of the outer shell from the TDV. The explosion causes a deceleration of 5,000g. Terrabrakes are deployed on the aft portion of the package to control the depth of soil penetration by the antenna base upon soil impact. Figure 2 illustrates what occurs at the time of impact. The photograph shows the antenna automatically deployed, restrained by the terrabrakes, while the main sensor body breaks away and continues to a depth of several feet. This impact is a second deceleration amounting up to some 10,000g.

The crystal oscillator is located in the aft section of the TDV. It is inserted - if necessary just before the round is fired - into a cavity of circular cross section extending radially into the TDV. The cavity is closed off by means of a screwplate, which happens to be visible in Figure 2 just below the fins.

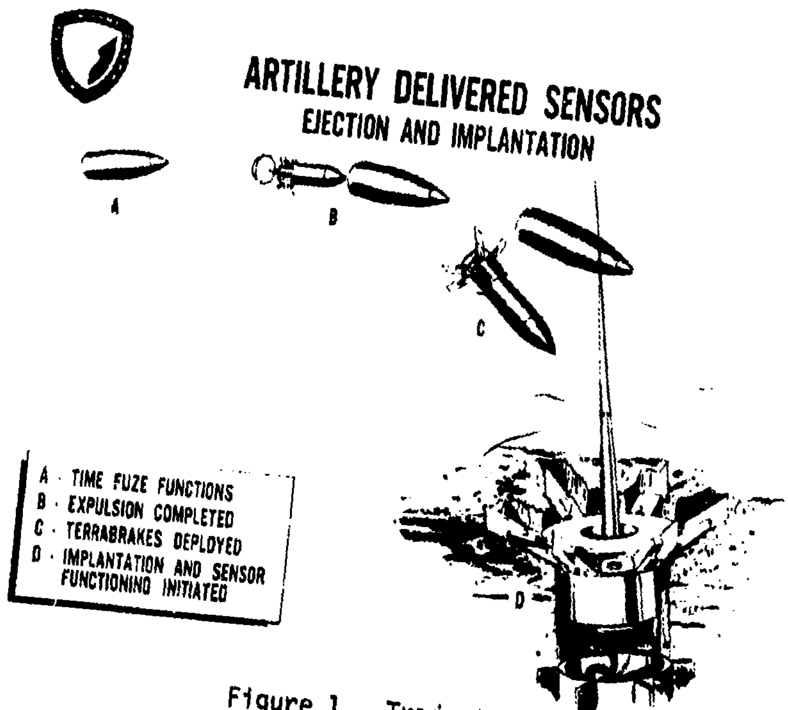


Figure 1. Trajectory

Figure 2. Implanted TDV

The problems to be resolved in designing a mass-producible crystal oscillator that guarantees that the frequency emitted by the sensor transmitter, after implantation, is within ±5 ppm of a predetermined value, are, obviously, not trivial. The difficulties are compounded further if this tolerance should be maintained for both FSK levels, mark and space, as well as for an optional analog transmission, regardless of ambient temperature in the prescribed range.

How the Electronics Command went about the solution will now be described. The discussion will first address the electrical and mechanical design of the oscillator and then that of the crystal unit.

OSCILLATOR DESIGN

Advanced remote ground sensors such as the Phase III transmitter or "common module" deployed in Southeast Asia were specified to have a ±30 ppm transmit frequency tolerance under operating conditions which included 1000g (6 msec) shock for air delivered units and a limited operating temperature range of 0°C to 60°C peculiar to that geographical area. Specification of the Phase III transmitter at ±30 ppm was the result of a compromise between desired narrow channel bandwidth (a large number of channels) and state-of-the-art of miniature Voltage Controlled Crystal Oscillators (VCXO) at that period in time.

Recognizing the need for a ±5 ppm oscillator stability to improve system performance capability, effort was initiated, first to develop a VCXO for narrow (0°C to 60°C) temperature range operation and air delivery usage (2). In anticipation of worldwide deployment needs, however, the temperature range requirement was soon changed to -40°C to +75°C, with the highest shock level (1000g) still determined by the airdrop delivery. When, finally, artillery delivery emerged as a highly desirable mode of sensor deployment, the oscillator development effort was redirected to meet the requirements imposed by the TDV environment.

A Phase III transmitter plug is shown at the top in Figure 3. A cavity, seen in the figure with lettering on its walls, contains the discrete components of the original ±30 ppm frequency tolerance VCXO operating in the 20 to 22 MHz frequency range. Channel selection was accomplished by crystal replacement, with access at the end plate of the plug. At the lower left is shown a retrofit hybrid microcircuit VCXO assembly which was developed and built at ECOM to demonstrate the feasibility of meeting a ±5 ppm overall frequency tolerance. Several of the Phase III transmitter plugs were modified using these oscillators, with ECOM-built crystal units. These met the requirements and successfully passed the REMBASS DT/OT II tests in June 1974.

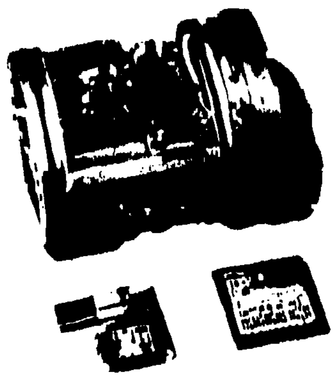
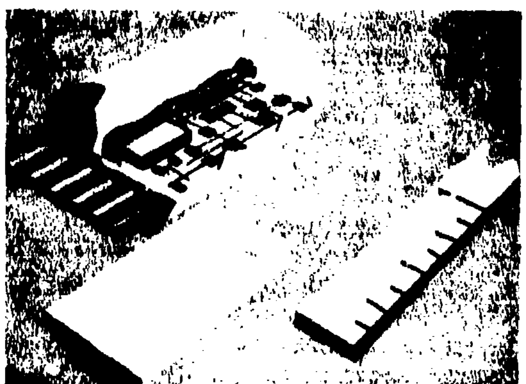


Figure 3. Phase III Transmitter Plug and High Stability VCXO

A sample of the extended temperature range (-40°C to +75°C) oscillator, developed subsequently, is shown on the lower right in Figure 3. It was destined to be incorporated into a completely redesigned transmitter plug, still within the overall size constraints of the original Phase III plug. The increased complexity of the device apparent in the photograph is due to the additional circuitry required to compensate for the excursions of the crystal frequency as a function of temperature. (The best oscillator stability attainable over the wider temperature range, without compensation, is in the order of ±15 ppm for airdrop environment and about ±20 ppm for artillery delivery, if production tolerance should be kept within still reasonable limits.)

Five sample units of this latter design were constructed within ECOM, again using ECOM-built crystal units, and delivered to PM-REMBASS. A powerful temperature compensation technique, to be described later, which lends itself to ease in manufacture and allows a reasonably large crystal angle tolerance,was employed to meet a ±2 ppm frequency/temperature stability requirement. An additional ±3 ppm was permitted for the effects of shock, 6 month aging and other frequency error contributions of lesser importance. The unit has capability for both digital FSK and analog modulation. Deviation sensitivity is 500 Hz per volt and deviation linearity is better than 1%. Not optimized for power consumption, the unit consumed 85 mW and required a bipolar 9 V regulated supply voltage. The total drain on two 15 volt batteries due to this oscillator is about 180 mW, if the dissipation in the regulators is included. (This has now been reduced to 50 mW and the need for a bipolar supply eliminated,as will be described below.)

Circuit techniques evolved in the development of this early thick film hybrid Temperature Compensated Voltage Controlled Crystal Oscillator (TCVCXO), augmented by computer-aided-design techniques, and experience gained in shock testing of both the package and microcircuits established the basis for the current design of the gunhardened TCVCXO. An artist's conception of the TCVCXO module is provided in Figure 4. Intended for insertion into a cavity accessed from the side of the TDV, the molded module has the geometry of a truncated cylinder. Following insertion of the TCVCXO module into its PC connector, the other, smaller, part of the truncated cylinder is wedged between the module and cavity wall to secure the two sections.



REMBASS TCVCXO MODULE

Figure 4.

Two 0.030 X 0.850 X 1.525 inch Alumina substrates comprising the linearized VCXO section and the compensation sections respectively are bonded back to back, with the circuitry protected and hermetically

sealed by thick-walled metallic lids. The rectangular geometry of the recently developed microcircuit-compatible ceramic flatpack crystal may be seen in the exposed linearized VCXO section in Figure 4. The crystal unit is situated such that the axis of rotation of the projectile passes through the center of the crystal and normal to its larger surface, thereby minimizing centrifugal forces under the rotational acceleration of 322,000 rad/sec^2. Initial air gun tests of mock-up models have indicated the capability of this configuration to survive a 20,000g 3 msec shock level. Investigations on the ruggedization of the thick film hybrid microcircuits were conducted and established design and fabrication guidelines for wire interconnections, thick film resistors, substrate, and chip bonding methods for satisfactory performance at the high shock levels. Tests have indicated that the microcircuits used here can be fabricated to survive a 30,000g shock environment and suffer no degradation, even without the use of epoxies for encapsulating individual active devices, nor the entire circuit. The program for ruggedization of the most critical component, the crystal unit, will be described later.

The functional block diagram of the TCVCXO illustrating the design approach is shown in Figure 5. An antiresonant Pierce type crystal oscillator circuit was selected to provide an optimum in stability performance. The oscillator contains a voltage variable capacitance in series with the crystal unit, by means of which the output frequency is changed in response to variation in the voltage applied to this capacitance. The relationship between output frequency and applied voltage is normally nonlinear. To permit simultaneous functions of digital FSK or linear analog modulation, frequency compensation and frequency trim, linearization of the VCXO tuning characteristic to better than 5% over a deviation range of 100 ppm is required. This is accomplished by a diode function generator (DFG) design which produces a two-segment voltage transfer characteristic having a nonlinearity approximating the reverse of the oscillator's frequency-voltage tuning characteristic. The number of required segments is related to the degree of linearity required, e.g., the 1% linearity previously specified on an early TCVCXO required six-segments. Functional trimming of thick film resistors in the network, with the circuit energized, guarantees achieving the exact required performance.

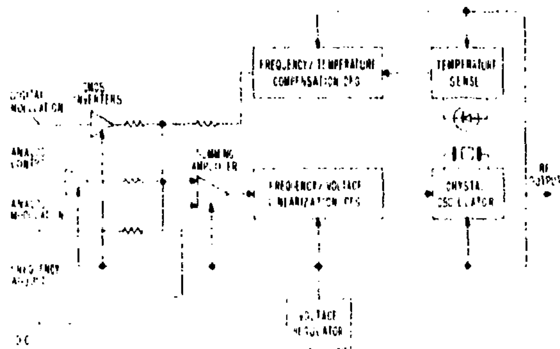


Figure 5. TCVCXO Block Diagram

A more conventional approach to VCXO linearization was considered and found to possess undesirable characteristics. For example, 5% linearity at 100 ppm frequency deviation may be obtained from a 20 MHz VCXO by introducing an inductor in series with the crystal unit, in addition to the varactor. It can be shown, however, that this causes large, unpredictable contributions to the VCXO frequency temperature characteristic, and requires additional tuned circuits to be incorporated to suppress possible spurious oscillations. The overall effect is a significantly reduced stability.

The temperature compensation is accomplished by a six-segment DFG which produces both positive and negative slope segments to approximate the required cubic frequency-temperature compensating function. The compensation DFG is driven by a temperature sensing circuit employing the repeatable temperature characteristics of a silicon diode to sense the package temperature. Crystal units having lower to upper tuning point deviations, ranging from 10 ppm to 30 ppm may be compensated to within ± 2 ppm with this method. Existing compensation techniques require much tighter control in crystal temperature behavior.

Inasmuch as power consumption is a very important consideration, a major objective of this development was to limit the power consumed by the entire unit to less than 50 mW at the maximum supply voltage of 15 volts. The largest single contribution to the overall power consumption of the TCVCXO is the regulator which consumes over half the total power at the maximum battery voltage of 15 volts. The power distribution among the major sections of the current TCVCXO design, as shown in Figure 5, are 9 mW for the oscillator proper, another 9 mW for the temperature compensation circuit and 7 mW for the linearization DFG including input circuitry. These comprise a constant load of 25 mW at the regulator output. The regulator may consume between 10 mW and 28 mW of power depending on the dc supply voltage which is specified to have a range of 10 to 15 volts. This voltage range represents the family of batteries being considered or that are in development for this system. IC regulators with typically 3 volt input differential and relatively large power dissipation were found unuseable in the TCVCXO. Power consumption in the crystal oscillator was minimized by a method of stacking the oscillator and buffer stages. Low current devices and high valued resistances were employed whereever possible throughout the linearization and compensation networks to save power. Effort is, however, continuing to further reduce the total power consumption in this device.

A sample of a completed compensation section microcircuit is shown in Figure 6. The linearized VCXO microcircuit is shown in

gure 7, except that capacitors and active devices have not been mounted. A ceramic flatpack crystal is shown positioned on the substrate over the metallized area to which it will be bonded.

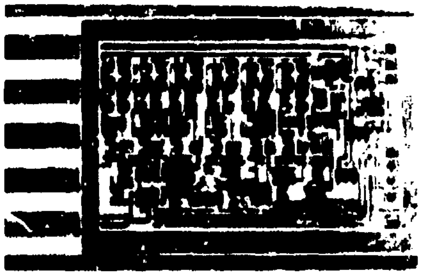


Figure 6. Thick Film Compensation Microcircuit

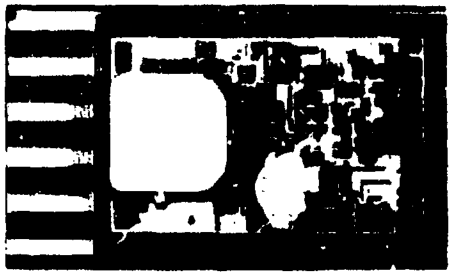


Figure 7. Thick Film Linearized VCXO Microcircuit

A comparison of TCVCXO compensated and uncompensated characteristics is shown in Figure 8. Compensation to approximately ±1 ppm is indicated, a compensation ratio of 8 to 1 for the particular crystal used, and is typical of recent breadboard units compensated. The compensation procedure requires prior knowledge of the frequency-temperature characteristic of the particular crystal unit to be used. Based on it, the proper values of one or two resistors in the circuit are determined, graphically or by calculation, and adjusted to these values by trimming at room temperature, all other resistors having already been trimmed to standard values. A single temperature run of the completed oscillator, to confirm the attained stability, is required. Indications are that ±2 ppm stability will be readily obtained in actual production units. Compensation techniques employed prior to this development required one or more temperature runs of the entire oscillator - a major cost factor - for achieving the desired stability.

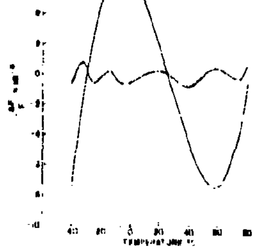


Figure 8.

CRYSTAL DEVELOPMENT FOR THE REMBASS OSCILLATOR

The requirements of REMBASS dictate a set of crystal specifications which crystal manufacturers were unable to meet at the inception of the program; and there are, to date, still no commercial sources for REMBASS crystal units. It has been clear from the beginning that minor improvements in the standard manufacturing techniques

would not suffice. Radically new designs and manufacturing techniques needed to be developed. This task was pursued in-house at the Electronics Technology & Devices Laboratory (ECOM). Manufacturing methods and techniques (MM&T) programs, to translate the advances achieved in the laboratory into a commercial pilot production line for REMBASS crystal units, are expected to be completed by the end of FY-78.

The three most challenging problems presented by the REMBASS specifications were the shock resistance, frequency vs. temperature behavior and aging (i.e., frequency vs. time) requirements. Our objective was to recognize, and find ways to eliminate, the mechanisms which cause noncompliance, and identify techniques that will make it possible to control the fabrication process to the degree necessary to achieve high yield. Figure 9 shows a flow chart of the major steps required to manufacture a crystal unit. The steps which were extensively investigated in connection with this program are cross hatched. The investigations which resulted in patentable new or improved processes are also indicated. The flow chart will be used as a rough guide to describe the work performed and results achieved.

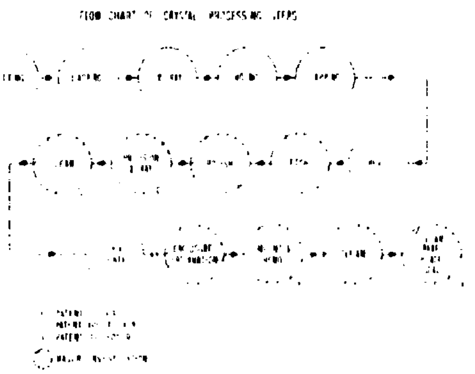


Figure 9.

A 20 MHz fundamental mode crystal resonator, as used for the REMBASS application, consists of a properly oriented quartz crystal disk of 0.64 cm (1/4 inch) diameter, 76 micron (0.003 inch) thick. When subjected to a 15,000g shock, its weight increases momentarily 15,000 times, causing enormous stresses to develop. If microcracks, fissures or scratches are present, such as might remain from the preceding cutting and lapping operations, the resonator will break. Moreover, damaged surface layers, if not properly removed, will significantly increase the aging rate of the crystal unit. The surface morphology was therefore studied extensively in order to determine the optimum lapping, etching and polishing procedures (3, 4). The amount of etch required to remove the damaged surface layer, and various polishing processes were investigated by scanning and transmission electron microscopy (SEM and TEM) and by reflection high energy electron diffraction (RHEED). The SEM and TEM micrographs and RHEED patterns revealed that the amount of etch necessary to remove damaged layers

was nearly ten times as much as the minimum specified by MIL-C-3098 (General Specifications for Quartz Crystal Units). Large differences in surface qualities were also revealed among crystals prepared with different polishing techniques. A combination of polishing variables which could produce a nearly perfect, defect-free surface was identified.

The frequency-temperature behavior of a crystal unit is determined, first of all, by the crystallographic orientation of the resonator blank, which is measured with an X-ray goniometer. It is also affected by a large number of secondary factors such as electrode geometry and mass, stresses due to mounting and bonding of the resonator to its supports, etc. The errors inherent in existing goniometers made the assessment of these secondary factors, which are significant for REMBASS crystals, very difficult. All uncertainty about the crystallographic orientation of the resonator was removed as a yield limiting factor when the X-ray goniometer accuracy was improved tenfold with the incorporation of a newly devised laser alignment system (5). A private company is already preparing a commercial version of this device for sale to crystal manufacturer

Surface contamination can lead to aging by several known mechanisms. If contamination equivalent to a single atomic layer of quartz is adsorbed onto the surface of a 20 MHz resonator, the frequency changes by 13 ppm, 13 times the permissible aging for a whole year. A cleaning procedure, therefore, had to be developed which is capable of producing near atomically clean surfaces.

After investigating numerous cleaning methods, using surface analytical tools such as Auger Electron Spectroscopy and contact angle measurements, a simple method for achieving the required clean surfaces was developed (3, 6). The method consists of a thorough precleaning followed by irradiation with short wave ultraviolet light and ozone. This UV/ozone cleaning procedure was determined to be capable of removing all contaminants which are commonly found on resonator surfaces, at least to within a small fraction of a monolayer. The UV/ozone cleaning procedure developed by us has been adopted by numerous crystal manufacturers.

It is apparent from Figure 3 that the enclosure used for the crystal unit in the assembly on the lower right provides an extremely poor fit to a microcircuit. The unit there was for low shock application; but the statement is equally applicable to the TO-5 enclosure that might be used for high shock environments. Moreover, the TO-5 construction does not lend itself to the type of final resonator processing shown to be essential for the crystal unit to meet the established aging requirement. A thorough analysis of applicable materials

and construction constraints led us to the design and development of a radically new crystal enclosure (7-9) as shown in Figures 10a and 10b.

The enclosure is a ceramic flatpack which consists of a frame with top and bottom lids. The frame is constructed by a multilayer ceramic technique, with buried layer metallizations for the electrical connections. The ceramic currently being used is alumina, and the feedthrough metallization is tungsten. It conveniently provides for a two point mount for low shock crystals and a four point mount, one in each corner, for high shock use.

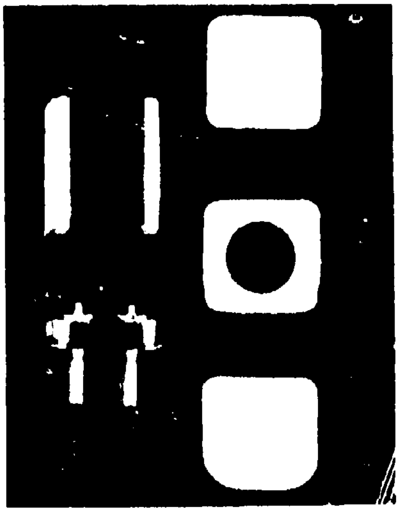


Figure 10a. Exploded View of Ceramic Flatpack vs. HC-42 Metal Enclosure

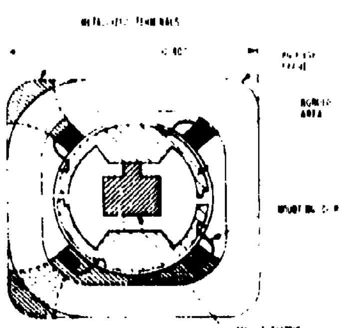


Figure 10b. Ceramic Flatpack Frame with High Shock Crystal

The major difficulty in utilizing ceramic materials in the past has been the lack of a strong, low-temperature, non-contaminating hermetic seal. During this enclosure development program, two new techniques for joining ceramic to metal were demonstrated. One method uses an aluminum gasket between two unmetallized alumina sealing surfaces; the other uses a gold gasket between sealing surfaces which are metallized with gold. Both seals are brought about by first cleaning the surfaces thoroughly (e.g., by the UV/ozone cleaning method described earlier) then heating the surfaces to about 300°C and applying sufficient pressure to deform the sealing gaskets. Leak rates of less than 10^{-13} STP cm^3/sec have been demonstrated. A commercial source for these enclosures has been established.

The techniques used for mounting and bonding, i.e., holding the resonator inside the enclosure, is certainly the most critical barrier problem in the design of high shock resistant crystal units. In our first experiments we consistently managed to convert the carefully prepared resonators into (quartz) sand during the first shock. Later designs showed that all units in a group of 20 crystals could survive 36,000g shocks in an airgun, but

their frequency-temperature behavior was highly irregular and unpredictable, and their aging poor, because of excessive stresses exerted on the resonator.

The problem of mounting and bonding the resonators in a manner that is strong, but also nearly stress free, was solved by developing and, through extensive investigations, optimizing a new bonding method called nickel electrobonding (6, 10-13). The standard bonding methods, conductive cement and thermocompression bonding, were found to be unsuitable for high precision, high shock 20 MHz resonators.

The nickel electrobonding process is performed by plating a layer of low internal stress nickel on the joint between the mounting clip and the quartz plate. The process offers the advantage that the clip can be strengthened subsequent to mounting, without increasing the mounting stresses, by also plating onto the clip a layer of nickel. Other advantages of this process are that, unlike cement bonded resonators which outgas, nickel electrobonded resonators can be vacuum baked at high temperatures, and unlike thermocompression bonded resonators, the process can be used on very thin resonators because it is performed without the use of high pressures and temperatures.

The steps of the nickel electrobonding process for low shock units are illustrated in Figure 11. For added support, the high shock resonators are supported by four mounting clips spaced evenly around the circumference of the resonator; and the electroplated area extends around the whole circumference of the blank, except for two narrow gaps which are necessary to electrically isolate the electrodes, thus effectively providing a nickel ring around the quartz disk comprising the resonator. Figure 10b shows the high shock crystal in the ceramic flatpack.

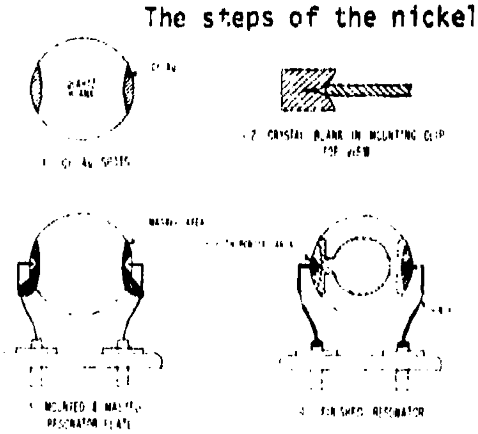


Figure 11. Nickel Electrobonding Procedure

The results of 1,000g shock tests showed early in the development program that Ni electrobonded resonators of the low shock design could survive 1,000g shocks without changing frequency by more than the allowable ±0.5 ppm (14). In more recent 15,000g shock tests, all units with Ni rings survived; half of the units changed frequency by less than the allowable 2 ppm, and the maximum change observed was 5.4 ppm. After these units were reshocked at 18,000g, again all survived, and

none changed frequency by more than the allowable 2 ppm. Early results of a finite element analysis of the resonator's behavior under high g loading have aided in the shockproofing of the crystal units.

In order to achieve the required smooth and predictable frequency-temperature behavior for the high shock design, very extensive effort was still required to determine the optimum geometry, thickness and orientation of the ring structure, as well as the geometry of the electrodes and of the resonator itself. The performance of the crystal units most recently prepared indicates that this has now been accomplished satisfactorily. Shock tests on units of this latest design have not yet been performed but should show further improved results.

The final step on the flow chart in Figure 9 is labelled Clean-Bake-Plate-Seal. In the conventional final processes of fabricating resonators, the resonators are cleaned in air, then baked, plated and sealed, all in separate vacuum chambers. During the transfer from one chamber to the next, the resonators are exposed to air. As is well known in vacuum science, when a clean surface is exposed to air, it adsorbs contamination from the air instantaneously. To meet the aging requirement, it was imperative that these last processing operations be performed in ultrahigh vacuum without exposure to air between operations. The merits of achieving low aging resonators by fabrication in ultrahigh vacuum, without venting between operations, had been demonstrated in earlier experiments by Hafner and Blewer (15).

Figure 12 shows an artists conception of the continuous, in-line vacuum system designed for manufacturing the resonators required by REMBASS. A patent has been issued on the system design (16). The system consists of a metal tube separated into five chambers by means

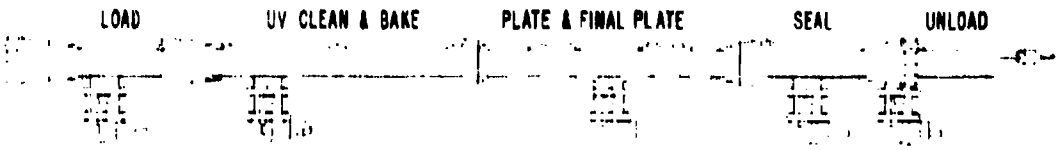


Figure 12. In-line Vacuum System for Final Processing REMBASS Crystals

of gate valves. The unelectroded resonators, mounted and bonded into the frame of the ceramic flatpack enclosure, placed in a carrier along with the flatpack covers, are inserted into the load chamber and exit via the unload chamber as completed, hermetically sealed crystal units. Baking and final UV cleaning, plating and sealing are performed in the other three chambers, which remain under vacuum continuously. The system, which includes several other novel aspects, will be constructed by a contractor. Award of contract is considered to be imminent.

Aging data on a group of 20 ea 20 MHz crystal units of the low shock design, in metal enclosures, fabricated in essentially similar fashion in our ECOM facility, has shown an early average aging rate of 5×10^{-8}/month for the first three months, levelling off to 2×10^{-8}/ month in the fourth month. This rate will satisfy the REMBASS requirement. Initial indications of the aging behavior of similarly processed 20 MHz resonators of the high shock design show no significant differences compared to the low shock units. However, long term aging data is not yet available. Also, there is no data on hand, as of this writing, on units in ceramic enclosures. The latter are expected to at least equal the aging behavior of metal enclosed units if processed in the manner described.

CONCLUSIONS

The REMBASS and FAALS data transmission systems require a voltage controlled quartz crystal oscillator that maintains the frequency of the signal transmitted by the artillery emplaced sensor within ±5 parts per million of a predetermined value over a temperature range of -40°C to 75°C, for a minimum period of six months. Shock levels of 15,000g are expected to be encountered during the artillery delivery. Extensive investigation on both the quartz crystal unit and the oscillator has resulted in designs that, based on independent tests, will be capable of meeting the systems requirements.

The crystal units employ AT-cut resonators in the 17 MHz to 22 MHz range, mounted into ceramic flatpack enclosures by nickel electrobonding techniques which provide an adequately rigid yet stress free support structure. The resonator and support structure designs are optimized for providing the required shock resistance as well as a smooth third order frequency temperature characteristic suitable for compensation by means of a standardized six-segment diode function generator in the oscillator. All process variables have been identified and techniques developed to control them to the extent necessary to assure high yield in production. The overall concept and key elements of a modern production facility for these crystal units have been defined. The thick film hybrid oscillator is housed in a 1.5 inch long, 1 inch diameter plug for easy insertion into the Terminal Delivery Vehicle. Survivability in the high g environment and conformance to the electrical requirements have been established. Battery drain is 50 mW at the upper end of the 10-15 V supply voltage range. Fully operational oscillator models incorporating all the design aspects developed are being prepared for confirmatory testing. Pilot line production sources for crystal units and oscillators are being established.

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